Parametric Armatures for Handwork

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> Machines will lead to a new order both of work and of leisure.[1]
> - Le Corbusier

Digital fabrication has emerged as a highly visible example of what some would call the "digital revolution" in architecture, with promises of direct linkages between digital design and physical production, or as William Massie puts it, "the ability to move directly from information to work."[2] Similarly, the rhetoric associated with most digital fabrication projects explicitly or implicitly heralds a bright future of precision, ease, economy and flexibility. What most digital fabrication projects obscure is the necessary and often messy reliance on manual processes in the actual realization of built examples. This paper problematizes the seeming seamlessness of digital fabrication, and presents two research projects that seek to foreground a necessary and productive interplay between digital and manual processes.

Digitally controlled machines are wonderfully adept at cutting or shaping individual components with precision and repeatability. But these components still require vast inputs of manual labor in post-processing including cleaning, finishing, fastening or clipping elements into sub-assemblies, transportation, arrangement and final assembly on site. Few high profile digital fabrication projects reveal the importance (and difficulty) of these manual interventions, preferring instead to reinforce the primacy of the machine as the main agent of production. Recent examples, like the work of Gramazio & Kohler in Switzerland point toward even greater reliance on automation with robotic assembly methods that promise to further displace manual modes of construction. While few digital fabrication projects acknowledge the necessary intervention of manual labor, fewer still are aimed precisely at generating a useful and rewarding collaboration between the intelligence of the machine and that of the hand. This paper aims to enrich the current discourse on architectural production by recasting the relationships between digital design and fabrication on the one hand, and manual assembly and construction on the other.

Unlike many digital fabrication projects that focus on the direct manipulation of raw materials to produce custom shaped components, often in series with minute variations, the two projects described here: *Scrapwood Shells*, and *Brick Veils* (Figure 1), are aimed at parametric arrangements of stock materials. Short lengths of standard framing lumber and common masonry units are assembled manually, while it is the relationships between these repetitive units that are digitally varied. Further, while most digital fabrication projects require materials that are 'neutral' in their qualities –i.e. predictably flat and of uniform thickness, these projects aspire to being adaptable to material variation, and even to the use of scrap or recycled materials.

The operating principle of both projects is to deploy parametric design and digital fabrication not to directly fabricate components themselves, but rather, to create intelligent *jigs* that can be used to organize pieces of wood and bricks in unique, efficient and expressive forms. Central to this approach is the primacy of choreographed activities that engagingly exploit manual dexterity.

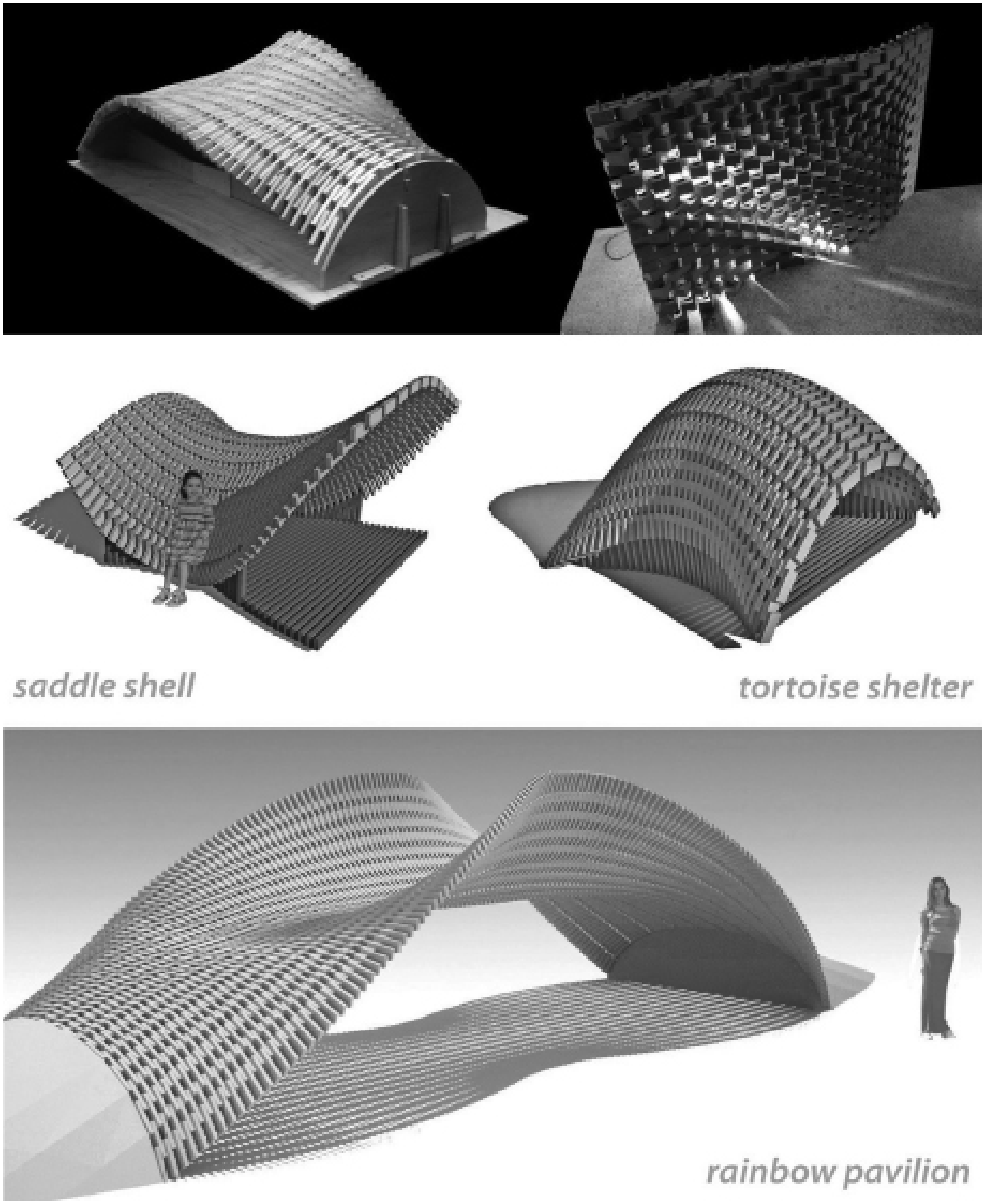

Figure 1: TOP Scrapwood Shell (left) and Brick Veil prototype (right). MIDDLE and BOTTOM: Scrapwood Shells: A family of forms shaped by material constraints and structural form-finding. (images by Rob Corser except Brick Veils by Cory Mattheis)

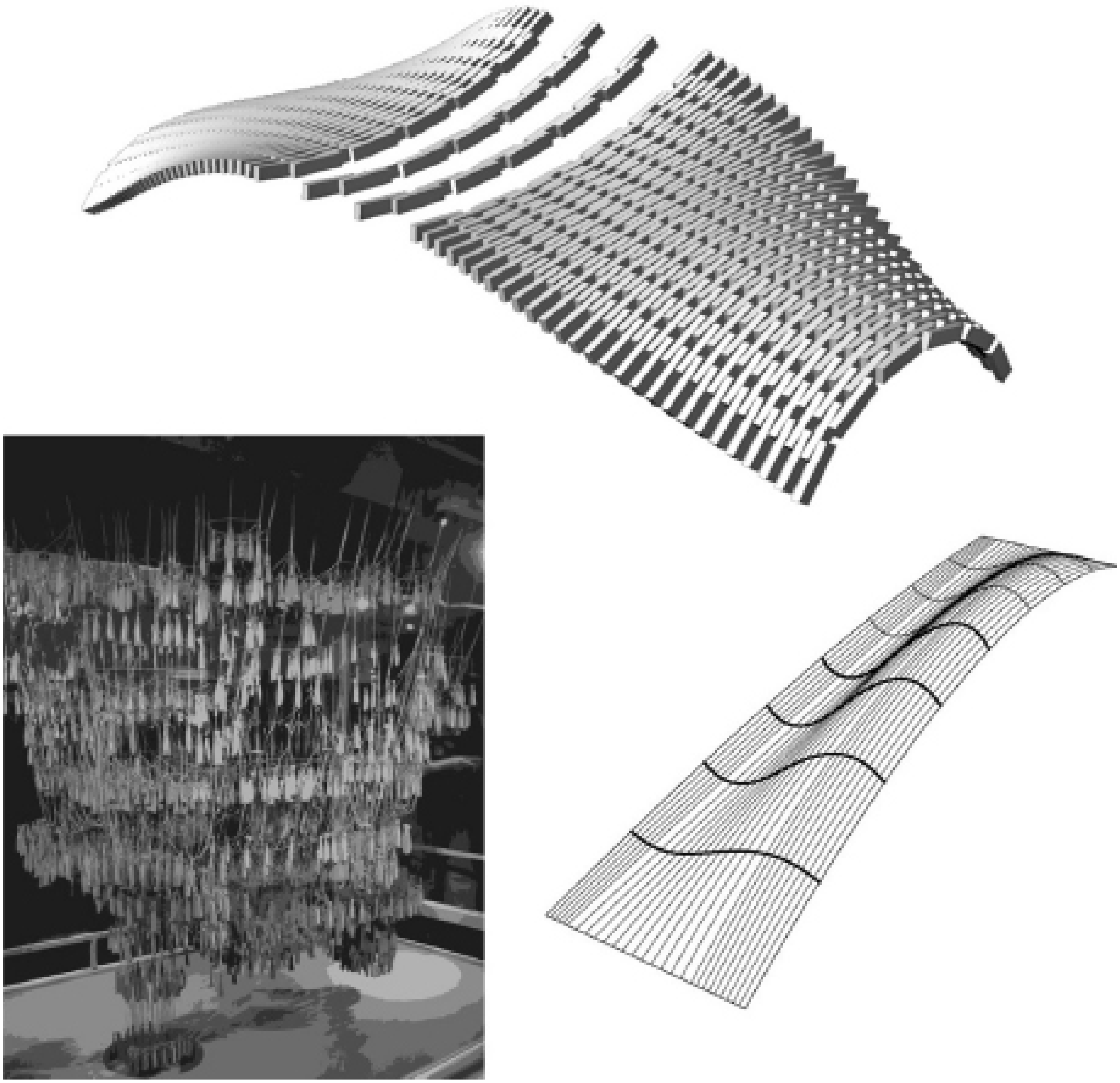

Figure 2: TOP: Scrapwood Shell design and construction concept diagram: curved courses are aggregated along a catenary path. BOTTOM: Structural form finding precedents. Left: Antonio Gaudi's hanging chain model of Sagrada Familia, Barcelona, ca. 1925. Right: Diagram of Eladio Dieste's 'gaussian' shells. (images: Rob Corser)

While both Scrapwood Shells and Brick Veils remain demonstration projects, they are intended to serve as prototypes for future methodologies that will benefit from a more productive collaboration between parametric design, digital fabrication and physical construction.

SCRAPWOOD SHELLS: PROJECT OVERVIEW

Scrapwood Shells, a faculty research project, consists of designs for a series of small shelters that will serve as part of an environmental education effort focused on the re-use of wood scrap from construction waste.[3] The designs illustrated here include two small enclosures for camping or play called the Saddle Shell and the Tortoise Shelter, along with a larger bridging structure, potentially useful for group activities, called the Rainbow Pavilion (Figure 1, Middle and Bottom). The Scrapwood Shells project employs a parametric approach that is not tied to any specific formal solution, but instead generates a flexible construction system that is adaptable to different sizes, shapes and functions.

These small shelters are designed to highlight the re-use of scrap lumber, and to explore the sculptural beauty and structural efficiency of thin-shell curved forms that maximize the use of the scrap material while minimizing weight. More than a unique approach to design, the project also serves as a community based service-learning opportunity in which students and community members are brought together around the issues of recycling and green design through direct participation in a series of events crucial to the Scrapwood Shells' design and construction. These events include: a digital design charrette during which forms are shaped to accommodate functional and site requirements; scrap material collection activities; sorting and cutting scraps to length; site layout and foundation construction; and finally, assembly of the shell itself. The shelters are built on site, like masonry vaults, using digitally fabricated jigs that are lightweight, portable and easy to use.

The Rainbow Pavilion is the most structurally ambitious design option explored for the Scrapwood Shells project. It is inspired by the long history of research in structurally efficient, thin-shell forms, most of which pre-dates the use of computers for design, analysis or fabrication. Antonio Gaudi's well known hanging chain models for the vaulting of Sagrada Familia cathedral in Barcelona (Figure 2, bottom left) were the inspiration for later, and more daring experiments in what might be called 'inversion,' carried out by engineers like Frei Otto and Heinz Isler. Using physical models of string, fabric or chains that, when inverted, arrive at an equilibrium shape under the force of gravity, these designers were able to achieve efficient structural curvature in a variety of shapes. Many of these forms, like Gaudi's, are called 'synclastic' because the direction of curvature in any two opposite cross-sections is always the same.

The work of Uruguyan engineer and builder Eladio Dieste also perpetuates the long tradition of Catalan masonry construction that includes Gaudi. His vaults achieve structural efficiency differently however, largely through 'anticlastic' curvature wherein opposing cross sectional shapes curve in opposite directions. This is achieved in many of his projects by theoretically lofting a sinusoidal (broadly 's' shaped) cross section along a path of funicular curvature (Figure 2, bottom right). The resulting shape, what Dieste calls a 'gaussian' shell, has areas of both synclastic and anticlastic curvature.

Building upon these approaches, all of the Scrapwood Shells variations are formed by taking parabolic cross-sections (consisting physically of strings of wood blocks), and aggregating them along a path whose shape is that of a hanging chain, or catenary curve (Figure 2, Top). Both the cross section and path curves are mathematically derived. Along the length of the catenary path curve, each course of wood blocks is incrementally varied, in the shape of a parabola that slowly opens then closes.

In the case of the Rainbow Pavilion, the resulting form is an arch whose curvature transitions from synclastic at the support ends, to anticlastic at the middle. Variations of this shape were studied structurally using finite element analysis to determine which parabolic shapes and what degree of cross-sectional opening and closing generated the best results. This approach, while inspired by Dieste's gaussian forms, is extended by the opportunity for iteration and refinement offered by digital design and analysis.

Further, programmatic, site and aesthetic options and constraints (like overall width, span and height off the ground) are integrated with these studies of structural efficiency in a fluid process of give and take during the parametrically enabled conceptual design process.

HANDWORK AND TEAMWORK: PARAMETRIC CHOREOGRAPHY

Beyond employing volunteer team members for handwork at the stage of material collection and re-cutting scraps to consistent length, the construction of the Scrapwood Shells is aimed at productively linking digital design with manual assembly techniques at several scales. The Scrapwood

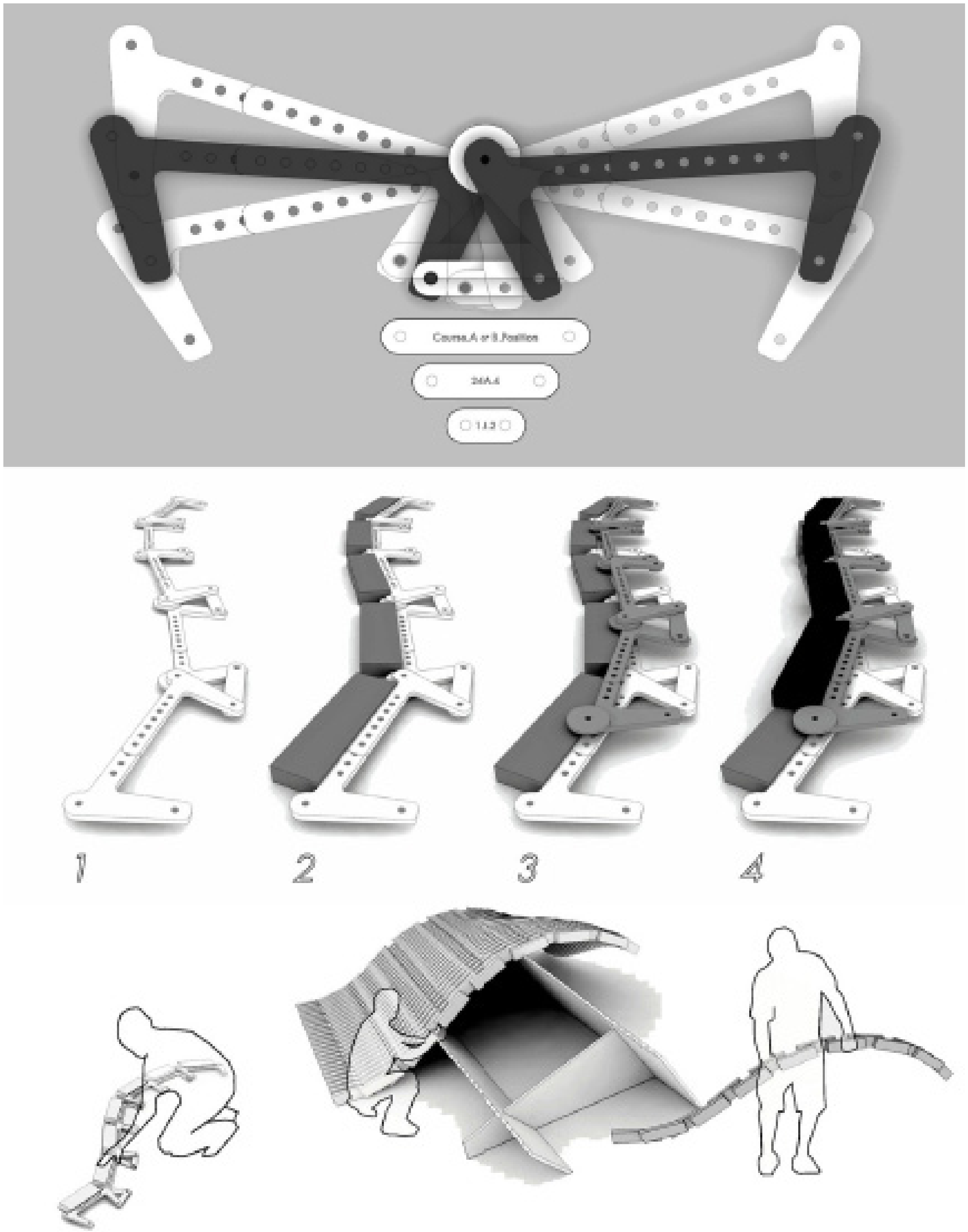

Figure 3: TOP: Diagram of the Jig shown in various positions. MIDDLE: Assembly of courses using adjustable jigs. 1. Bottom course jig is set with keys. 2. Wood blocks are set. 3. Upper course jig is placed and keys are set. 4. Upper layer blocks are glued and pneumatically nailed to bottom blocks. BOTTOM: Final shell assembly -courses are formed in jigs on left, and arranged on rail armature on the right. (images: Rob Corser and Scott Crawford)

Shells are built by small teams of volunteers working with sets of jigs and guides. These tools are digitally fabricated and are adjustable to accommodate each project's changing material parameters: different lengths of scrap wood, different spacing between blocks, etc. The reusable jigs are placed on a horizontal work surface, either the ground or a large worktable. Inserting spacers, called 'keys' in each position on arms along each of the two layers, sets the jig's curve for each 'course' of blocks (Figure 3, Top and Middle). The keys are gathered on cable loops -like key rings -that keep them in order, and they are coded so that a particular combination will correspond to the curvature of a particular course.

The construction process proceeds as follows: keys corresponding to the first course are set onto pegs on the bottom jig's adjustable arms, thus fixing the jig into a particular form, and wood blocks for the bottom of the course are set in place. The jig for the top of the course is fixed to the bottom jig and keys are placed to adjust its curvature (which is always slightly different from that of the bottom course as they will form part of a continuously changing system). Glue is applied to the area of overlap between blocks, and the wood blocks for the top layer of the course are put in place. Narrow gauge ring shank nails are pneumatically driven to hold the two layers together while the glue sets. The course is removed from the jig, and set aside for later assembly with other courses on an armature (this process will be described in the following paragraph). The previously used keys are removed from the jig and the next ones on the keychain are installed, corresponding to the curvature of the next course. Wood blocks are installed, glued and nailed, and the process is repeated.

Assembly of the completed courses into the final shape of the Scrapwood Shells proceeds from one end to the other, attaching one course to the next along a simple stepping armature of rails that are digitally cut from layers of three-quarter inch plywood (Figure 3, Bottom). The layout and construction of foundations and guides are the only activities requiring specialized surveying and construction skills because the supports must be carefully aligned and firmly supported with temporary bracing. Proceeding from one end, each new course is aligned, glued and screwed to the previous course along the rails.

Once the shell is complete and the glue set, the rails can be removed and the shell becomes self-supporting. While some settling may occur due to the adjustment of shell members to one another or the seating on foundations, these relatively small movements are inconsequential to the overall performance of the structure. Due to the highly repetitive system, the shell is robust, and visually dense, so that minor discrepancies fade into the overall structural and visual system. Even discrepancies in the alignment of blocks within the courses, or between one course and the next are structurally acceptable and make little visual impact.

While this method might seem laborious when compared with typical claims about the ease of digital fabrication, this is exactly the point. It requires team members to work together in careful processes according to a parametrically enabled choreography of actions. Some instruction and oversight is necessary, and care and accuracy are required, but no special training and little prior construction experience are needed. What is important here is that the construction process is designed to employ many hands in purposeful activity that, like the barn-raising events of previous generations, brings members of a community together and rewards their work with a handsome and useful object.

As a community building effort, people with a wide range of skills, backgrounds and physical abilities can all participate, and the emerging curved forms have an immediate visual appeal–sparking curiosity and giving a sense of satisfaction with the work. A scale prototype of the Rainbow Pavilion, an eight foot long bench (Figure 1, left), has been constructed for testing in advance of the first full size installation. The adjustable jig worked flawlessly in this prototype, and the bench is currently undergoing structural load testing to verify expectations about stability and structural performance.

BRICK VEILS: PROJECT OVERVIEW

Brick Veils is a student-initiated collaboration that pushes the approach and methods of the Scrapwood Shells project into new territory, both materially and structurally. The focus on facilitating sculptural surface manipulations is extended here to include modifications of surface porosity achieved through sequential rotations of the brick modules (Figure 4). This added dimension of complexity introduces

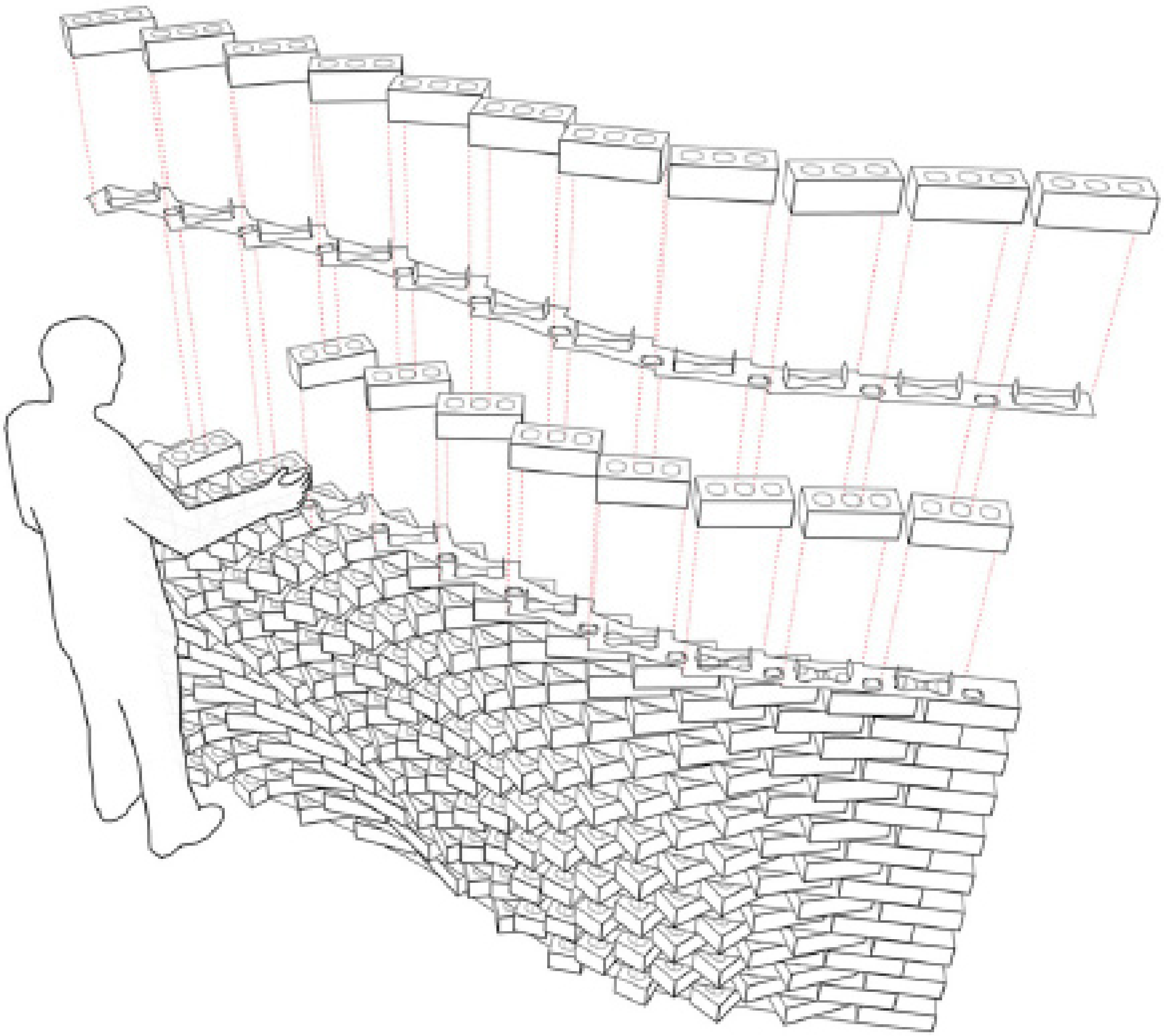

Figure 4: Diagram of Brick Veils system and assembly. (images: Cory Mattheis)

two constraints: first, the surface cannot act as a spanning shell in a horizontal orientation and must remain a more-or-less vertical wall or screen, and second, the area of overlap between bricks in each course becomes highly variable and can lead to the necessity of additional structural support. The latter constraint led to explorations of a jig design that would remain in place to act as horizontal reinforcing within the joint between each course. While the jig for the Scrapwood Shells is flexible and re-usable, the jig for Brick Veils acts as both an aid in orienting and securing the bricks, and as an integral reinforcing system that is set permanently into the fabric of the Veil itself.

As with the Scrapwood Shells, once the digital intelligence of the parametric model is translated into the light gauge metal reinforcing jigs, the intelligence of the hand is deployed to place, adjust and load jigs and bricks into a mutually interlocking system. Beyond generating interesting visual and formal effects, the intention for the screen is to serve as a component in a hybrid ventilation system wherein tubes passing vertically through the system (acting also as vertical reinforcing) might carry a cooling fluid loop that can be tempered both by the bricks' thermal mass and by air passing through the veil's porous openings –like a car's radiator.

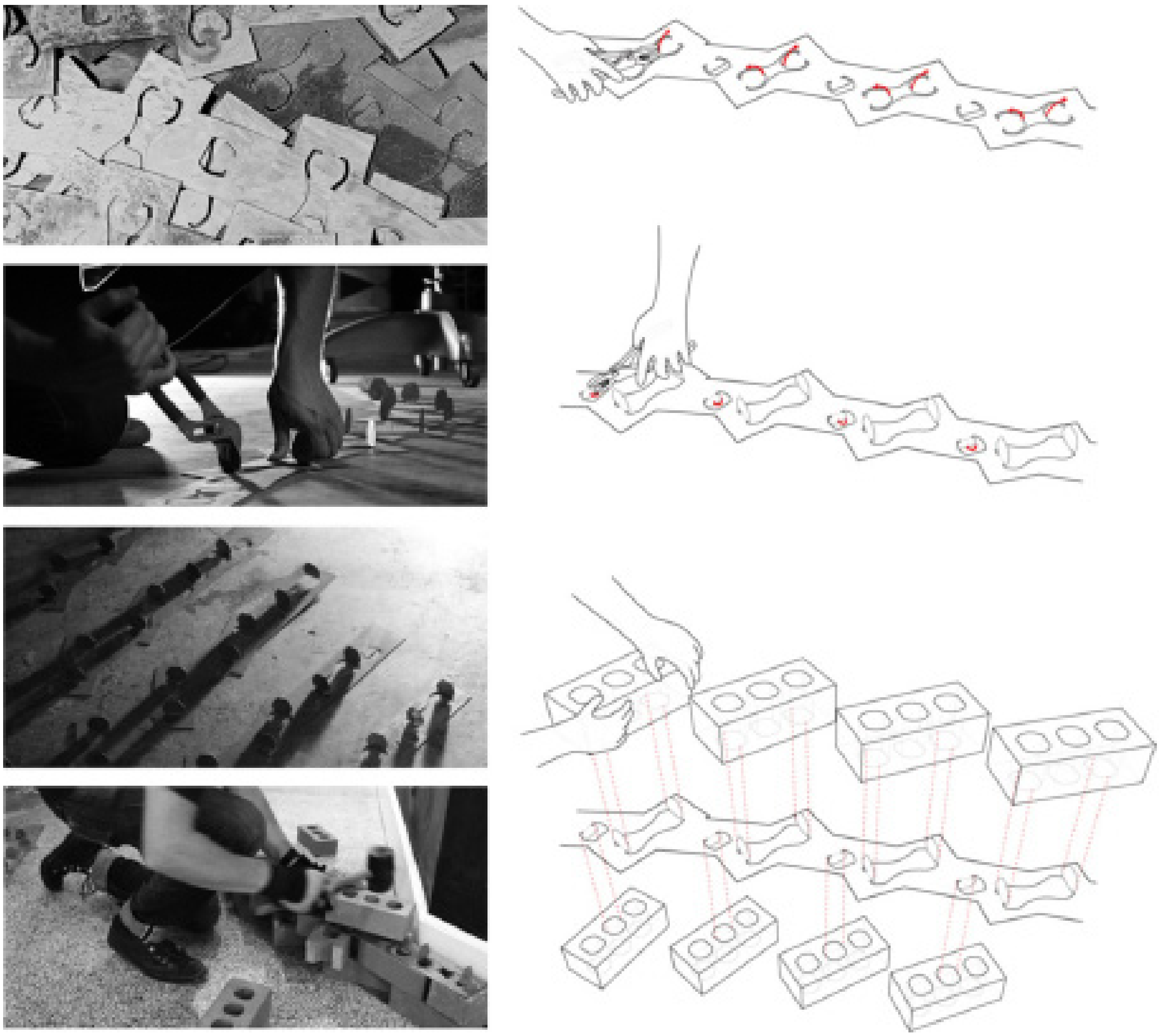

Figure 5: Diagrams and photos of Brick Veils jig and assembly sequence. (images: Cory Mattheis)

The design and fabrication process for the Brick Veils starts with a parametric model that can be adjusted to accommodate masonry units of various sizes. This digital tool is then manipulated to create the shape and ripples of the veil and to control areas and amounts of porosity –all in response to aesthetic, structural, environmental and other performance criteria. Once variations have been explored, tested and decided upon, cutting templates for the reinforcing jigs are exported. These templates are automatically numbered (numbering which is imprinted onto the jigs themselves) and laid out for waterjet- or laser-cutting from sheets of light gauge metal. Tabs are cut in the jigs to correspond with either centerline or edge holes in the masonry units. The perimeter shape of the jigs corresponds to the outside edges of the bricks as they align or rotate. After cutting, the jigs are stacked in order, and packaged flat for space efficient shipping. Once on site, the tabs are bent by hand using pliers, with the centerline tabs bending downwards and the edge tabs bending upwards (Figure 5, Top). Only the jig for the bottom course has no centerline tabs because it has no course below it - this jig is used to accurately lay out the overall position of the Veil on site. Once the first course is set in the bottom jig, the jig for the next course is set onto it, with the center tabs aligning in the center holes of the bottom course bricks. Subsequent courses of bricks and jigs are assembled similarly (Figure 5, Bottom). Manual alignment of the bricks is aided by both the tabs and tactile clues provided by the perimeter shape of the jig. If needed, adhesive can also be applied during assembly, and the jig can be imprinted with target areas for locating it precisely.

While the visual form of the Brick Veils is admittedly similar to that of other noteworthy projects that are based on robotic assembly (Gramazio & Kohler for example), the integration of manual labor not only promises greater affordability, but also accords better with the low-tech nature and existing labor pool of masonry construction. Beyond its expense, another major drawback of robotic assembly is that it reduces flexibility, requiring either pre-fabrication and transportation of heavy panels assembled in a factory, or transportation of cumbersome and delicate robotic equipment to the worksite itself.

By separating the intelligence of the machine from direct manipulation of the construction materials and loading it instead into manually operated jigs, similar formal results can be achieved more efficiently, and without displacing workers. Beyond these advantages, the intelligence of the hand can be maintained as a vital part of the construction process especially as it relates to the ability to make the tweaks, adjustments and judgment calls that are often necessary in the messy world of on-site construction. Finally, the Brick Veils jig performs two roles: both insuring the alignment and organization of the bricks, and contributing to its structural stability as a tension reinforcement between brick courses. While it may appear to be visually quite similar to robotically placed brick screens, in reality, the Brick Veils project embodies a radically different approach to fabrication that is founded on the hybridization of hand- and machine-intelligence.

CONCLUSIONS: WHERE DO WE STAND?

Situating the role of machines in architectural production has been a subject of debate since the industrial revolution, with much of the discourse focusing on issues of craft and authenticity. But lately, almost any discussion of tectonics or the cultural status of fabrication and construction has been replaced by a positivistic push to celebrate increasingly sophisticated and rarified processes like algorithmic design and robotics.

It is interesting to note that while Le Corbusier famously championed an architecture for the machine age, many of his buildings that were purportedly based on the latest concrete technology, were in fact built of traditional masonry that was stucco finished to resemble the newer material. Similarly, most cutting edge examples of the 'digital revolution' in architecture reinforce the primary role of new design and fabrication tools, while obscuring or effacing the actual necessity of manual processes in their making.

Rather than over-emphasize a dialectical opposition between hand and machine, we might follow the logic of David Pye, who concludes that it is more useful to draw a distinction between two modes of workmanship: the "workmanship of risk" (often, but not exclusively, associated with the hand) and the "workmanship of certainty" (often associated with the machine).[4] In the spirit of this more subtle distinction, the projects presented here argue for the cultivation of a more conscious interweaving of risk and certainty in design and fabrication processes.

And rather than stereotyping the essential qualities of hand or machine, we are better served to acknowledge that, upon close examination, the loci of risk and certainty might actually shift or blend in surprising ways. For example, in the Scrapwood Shells and Brick Veils projects, it is possible to conclude that the workmanship of risk is more evident in the creation and manipulation of the parametric digital models where multiple factors of form, function and performance are negotiated in ways that are not reducible to simple optmization routines. Similarly, the workmanship of certainty might be more visible in the manual assembly of blocks and bricks thanks to the guidance of digitally fabricated jigs. Ultimately then, the task before us is not to valorize or subvert either digital or analog modes of making, but rather to orchestrate richer hybrid processes that acknowledge the distinctive qualities of each, and weave them together in more enriching and meaningful ways.

ENDNOTES

1 Le Corbusier, *Towards a New Architecture* (London: John Rodker, 1927; New York: Dover Publications, 1986), 101. Citation is to the Dover edition.

2 William Massie, "Remaking In A Post-Processed Culture, "*Architectural Design*, v. 72, n. 5, (2002): 54. In the same article Massie states explicitly that "... recent advances in electronics and computer processing found in computer numerically controlled technologies now allow us to move directly from a computer model/ computer drawing to built form."

3 Every year wood frame construction in the United States generates more than seven million tons of lumber waste. A significant portion of this waste consists of short scraps of dimensional lumber that are not long enough to be used for horizontal blocking in 16 inch on-center construction and are usually discarded. The city of Seattle has recently announced a plan to collect and burn this kind of scrap in a downtown central heat plant. While the conversion of waste directly into energy diverts materials from the waste stream and provides useful power, it does so at the expense of immediately releasing all of the carbon that is stored in the wood into the atmosphere as carbon dioxide. A better approach would be to put the wood scraps into some other productive use, thus continuing to sequester the carbon for decades and, ideally, also engaging and informing the public about the issues of construction waste and recycling.

4 David Pye, *The Nature and Art of Workmanship* (London: Cambridge University Press, 1968), 20-21.